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Research Article

Use of linear transportation infrastructure rights-of-way as an ecological shelter: National asset estimate and stakeholder involvement

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Abstract

For a number of years, the rights-of-way (ROW) of several types of linear transportation infrastructure (LTI), such as roads, railways, waterways and power lines, have been regarded as possible shelter for biodiversity, notably local flora and entomofauna. For developing an informed general management policy of such an opportunity for species conservation and landscape connectivity, a fundamental prerequisite is to be aware of the ecological shelter potential available within LTI rights-of-way on a national scale. By considering the primary operating constraints of LTIs and their geometric characteristics, a GIS-based method was designed to approximate the linear extent and surface area of potential ecological shelter (PES), i.e. where actions could be implemented to provide sustainable shelter focused on local flora and entomofauna. At the scale of Metropolitan France, the minimum total surface area of PES amounts to 2,026 km^2; and its network spans over 88,094 km (39% power lines, 34% railways, 18% roads and 9% waterways). The State is the primary landowner of PES along operated networks (particularly railways) however over half of the assets (53.8%) fall under the responsibility of local authorities, concessionary companies and private landowners (notably power lines). These findings highlight the necessary involvement of State together with LTI operators, local stakeholders and landowners through partnerships aiming to implement the ecological shelter function of rights-of-way.

Key words: Biodiversity, conservation, geographic information system, habitat, management, network, Potential Ecological Shelter

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Introduction

Rights-of-way of LTIs and safeguarding biodiversity

The term right-of-way (ROW) defines the entire width of the reserved strip of land on which linear transportation infrastructure (LTI) is built (van der Ree et al. 2016). For a number of years, the rights-of-way for several types of LTI, such as roads, railways, waterways and power lines, have been regarded as possible shelters for biodiversity, in particular across those landscapes impacted by human activities which have led - or are still leading - to the destruction

of natural habitats and corridors (Baudry et al. 1995; Gardiner et al. 2018). To some extent, rights-of-way would be expected to improve the functioning of such damaged landscapes, by means of restoring connections between natural networks (hedges, riverside vegetation) or isolated habitats (Meunier et al. 1998; Michel et al. 2015).

Similar to natural corridors (e.g. rivers), manmade corridors like LTI rights-of-way can exhibit five main functions for species: habitat, conduit, source, barrier and sink (Burel and Baudry 1999; Forman et al. 2003). The role played by a corridor, whether or not it is natural, depends on the biological characteristics of the considered species, and also on its structure and place in the landscape (Burel and Baudry 1999).

The benefit of rights-of-way as a potential habitat is particularly relevant for native flora and entomofauna. Besides, there are numerous considerations numerous considerations at play, particularly concerning the conservation of threatened species, connectivity within landscapes (along rights-of-way and with neighboring green networks) and the provision of ecosystem services (De Redon de Colombier 2008; Hopwood 2008; Wagner et al. 2014; O'Sullivan et al. 2017; Villemey et al. 2018; Guo et al. 2022). Furthermore, in the context of climate change, biodiversity preserved and smartly managed within rights-of-way can provide opportunities for nature-based solutions (NbS) aimed at reducing the risks and consequences of extreme events (high/low temperatures, high precipitations, droughts, high winds…) on transport infrastructures, their quality of service and their users (Blackwood et al. 2022).

It can therefore be expected that implementing suitable management inside rights-of-way in the aim of developing their potential functions as habitats, conduits and possibly sources for re-colonizing neighboring degraded landscapes (Burel and Baudry 1999), could yield positive impacts. Such impacts would be felt not only at the local scale but also to a broader extent by limiting and compensating for the general decline of so-called common species, such as weeds and flying insects as well as downstream beneficiaries like birds (Hallmann et al. 2017; Richner et al. 2017; Stanton et al. 2018).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services points out the immediate opportunities to improve the current conditions of pollinators and maintaining the pollination service in road verges (IPBES 2016). This could be the case for all kinds of LTI rights-of-way and might also benefit other entomofauna species (Cardoso et al. 2020). With the ability to undertake general or specific actions within rights-of-way, LTI operators can become direct actors in local flora and entomofauna conservation and in the restoration of connectivity within landscapes. As an example and more broadly, in Sweden, the concept of 'responsibility species' was proposed by Helldin et al. (2015) in the aim of actively involving road and railway operators in the conservation of red-list species thanks to infrastructure verges.

On a global scale, states have committed to following the Kunming-Montreal Global Biodiversity Framework (UN Environment Programme, 2022), which is a contribution to the achievement of the 2030 Agenda for Sustainable Development (UN General Assembly, 2015). The framework calls for respect for the integrity of all ecosystems. Leveraging rights-of-way of LTIs to enhance biodiversity, ecosystem functions and services, ecological

integrity and connectivity, for the benefit of people and nature in degraded ecosystems, meets three targets (n°2, 11 and 12) for action by 2030. Hence such an initiative can support any State to comply with the Global Biodiversity Framework agenda.

Estimate of the national asset of potential ecological shelter

In order to develop relevant and consistent actions within ROW, and beyond, a general management policy in favor of biodiversity through the rights-of-way of various LTIs, it is essential to know their extent and the surface areas that can be realistically and effectively harnessed for the species of the local flora and fauna. This can be achieved by considering their structure and surroundings. However, restoring and/or developing corridor functionalities thanks to ROW cannot be an objective for all territories crossed by LTI networks. This point is notably true in the case of urban and industrial areas where, in addition to several local disturbances, rights-of-way are generally narrow, highly fragmented or perhaps nonexistent. Hence, extrapolation from the total LTI length (provided by annual compendia for example (EC 2022; CGDD 2019) cannot be the way to approximate the potential of ROW actually available at the scale of a large territory (e.g. country, region) and cannot therefore provide a reliable support to develop implementation strategies there.

Some LTI operators publish figures of the total surface area of their rights-of-way (Michel et al. 2015). Estimates however rely on their in-house approaches, which vary from one operator to the next and in most cases are not fully explicit. Some estimates comprise all green spaces, including those linked to human activities (e.g. motorway rest and service areas), while others do not. Some operators apply a fixed or variable ROW width around their LTI, while others use compilations from land registry maps. Lastly, not all operators have this estimate on ROW surfaces and moreover are unable to measure them over the short term. As a result, it is not possible to derive a complete, homogeneous and clear picture of the actual situation at the national, regional or local scale.

An analysis of cartographic databases available today (knowledge of LTI networks and crossed environments), combined with a consideration of the geometric criteria of LTI cross-sections and certain maintenance rules for the various types of ROW, offers one way to acquire this knowledge. This approach can provide a transparent estimation method, using well-founded uniform criteria throughout the assessed territory. It is adaptable to the main variations in LTI characteristics from one territory to another and to particular sections of networks. Hence, it can be reproduced at all territorial scales, regardless of their diversity, and handled by LTI operators and land managers from any territory equipped with mapping tools.

Consistent with this approach and its aims, a GIS-based method was designed to approximate, on a national scale, the length and surface area of rights-of-way parts from various LTIs which could be dedicated to local flora and entomofauna: a space hereafter referred to as potential ecological shelter (PES). PES concerns a part of biodiversity whose presence in ROW is not detrimental to the normal and safe exploitation of infrastructures. Additionally, areas considered as PES exclude ROW parts whose maintenance requirements are not compatible with

the respect of species' ecological needs and specimens' integrity (e.g. road and railway proximity strips), ROW parts that could create isolation or traps (e.g. road medians and interchanges), and ROW sections located in environments that are not conducive to the establishment of landscape connectivity with the surroundings (urban and industrial contexts). The development work was carried out and assessed in the French context, where cartographic databases dedicated to LTI networks and land uses are available, where the general view of ROW surface potential was heterogeneous and fuzzy, and where some figures from operators could serve as reference values to assess the GIS estimation process itself.

For many LTIs, the outer ROW boundaries often have complex shapes (e.g. property lines, topographical discontinuities, flood zones associated with watercourses), which cannot be properly and easily handled when estimating at the national scale. The ambition of the estimate was thus not to target the total maximum surface of PES, as acuity would be too low to demonstrate how the approach clarifies and supports decision-making. A more realistic perspective, which can offer greater direct utility for many situations in today's national and regional contexts, aims to assess the value of the minimum total surface of PES available at national scale. This means a guaranteed and more accurate floor value, as it has been calculated from the minimum incompressible width of different types of ROW. This constitutes a reliable minimum basis for developing policy and actions, while maintaining the possibility of refining data at lower levels with local stakeholder participation.

The national asset estimation method is presented below, along with the principles and tools. The results for all types of LTIs are detailed and discussed, notably in light of minimal pre-existing figures and stakeholders who could enable ROW become biodiversity shelters. This emphasizes the shared involvement among LTI operators as well as local stakeholders and landowners to implement the ecological shelter function of rights-of-way.

Materials and methods

Cartographic tools

The geographic information processing software used for this study was QGIS 3.4. The database employed for LTI networks was BD TOPO® (provider National Geographic Institute, IGN; design scale: 1:25,000) (IGN 2019). For the road, railway and power line network maps, the data were extracted from "Road network", "Rail network" and "Energy transport network" subfiles (version 2.2, January 2019), and for waterway network map, from the "Hydrography" subfile (version 3.0, April 2019) which allowed checking the actual navigability of each waterway segment. The national waterway operator (VNF) database served to delineate the State-owned domain. Figures from recent compendia on the total length of transport networks (Michel et al. 2015; CGDD 2019; EC 2022) were used to calibrate the compilation method with databases and ensure reliability for subsequent calculations (avoidance of double counting and omission of entities).

The database used for the forest cover was BD FORET® version 3 (provider: IGN; design scale: 1:25,000; update: November 2018 (IGN 2018)). This resource records the various types of plant and forest formations, according to the majority of species observed over areas larger than 0.5 hectares and at least 20 m

wide, primarily based on the rate of plant cover (e.g. ≥ 40% = closed forest). The Corine Land Cover database, hereafter referred to as CLC (provider: European Environment Agency; design scale: 1:100,000; update: 2012 (CGDD 2016)), was used for delineating the urban and industrial spaces.

Delineation of urban and industrial areas

Objects entitled "Continuous urban fabric", "Discontinuous urban fabric", "Industrial or commercial units and public facilities" and "Port areas" in CLC were collated and around the resulting urban polygons, a 200-m wide buffer was applied. In CLC, objects such as "Road and rail networks and associated areas" and "Rivers and waterways" often pass through the urban fabric without being considered part of it, hence becoming merged with it. The 200-m wide buffer was intended to cover (i.e. mask) the presence of LTI networks within the urban/industrial fabric, hence to exclude them from the ROW surface calculation. Its size was set as the minimum width covering the various types of LTI rights-of-way in a large city: tests were carried out on the conurbations of Paris (48.856°N, 2.352°E), Bordeaux (44.837°N, -0.579°W; 780,000 inhabitants) and Nantes (47.218°N, -1.553°W; 650,000 inhabitants).

LTIs and their specific ROW width

For each type of LTI, Fig. 1 schematically summarizes the location and extent of ROW parts considered in the estimate.

Power lines

Two types of transmission lines were considered for the calculation: high-voltage power lines (63 to 90 kV – hereafter referred to as HV lines) and very high voltage lines (225 to 400 kV – referred to as VHV lines). The ROW segments referred to as "Unspecified", "Unknown" and "Power down" in the database, as well as a short 150-kV segment, were not considered as they account for just 5 km at the national scale.

For power lines, a continuous linear land right-of-way only appears when crossing wooded areas (Fig. 2). In open contexts, their ground footprint is limited to the pylon footprint. Thus, for the PES estimate, the power line network is considered where it passes through forests and the width potentially available as an ecological shelter is the full ROW width.

In light of technical and safety requirements, the typical right-of-way width for a HV line where it cuts through woodland is 30 m, while VHV lines are assigned a 50-m width (Michel et al. 2015; François et al. 2018). These values have been verified on aerial views from the public databases Géoportail (www.geoportail.gouv.fr) and Google Earth (www.google.fr/earth/) in different forested areas in France: Ardennes (Northeast), Limousin (Center-West) and Landes (Southwest).

Waterways

Two types of waterways were considered for this calculation: shipping canals (artificial waterways), and navigable rivers (natural waterways). For both, the ROW can extend far from the bank, depending on local geomorphological conditions.

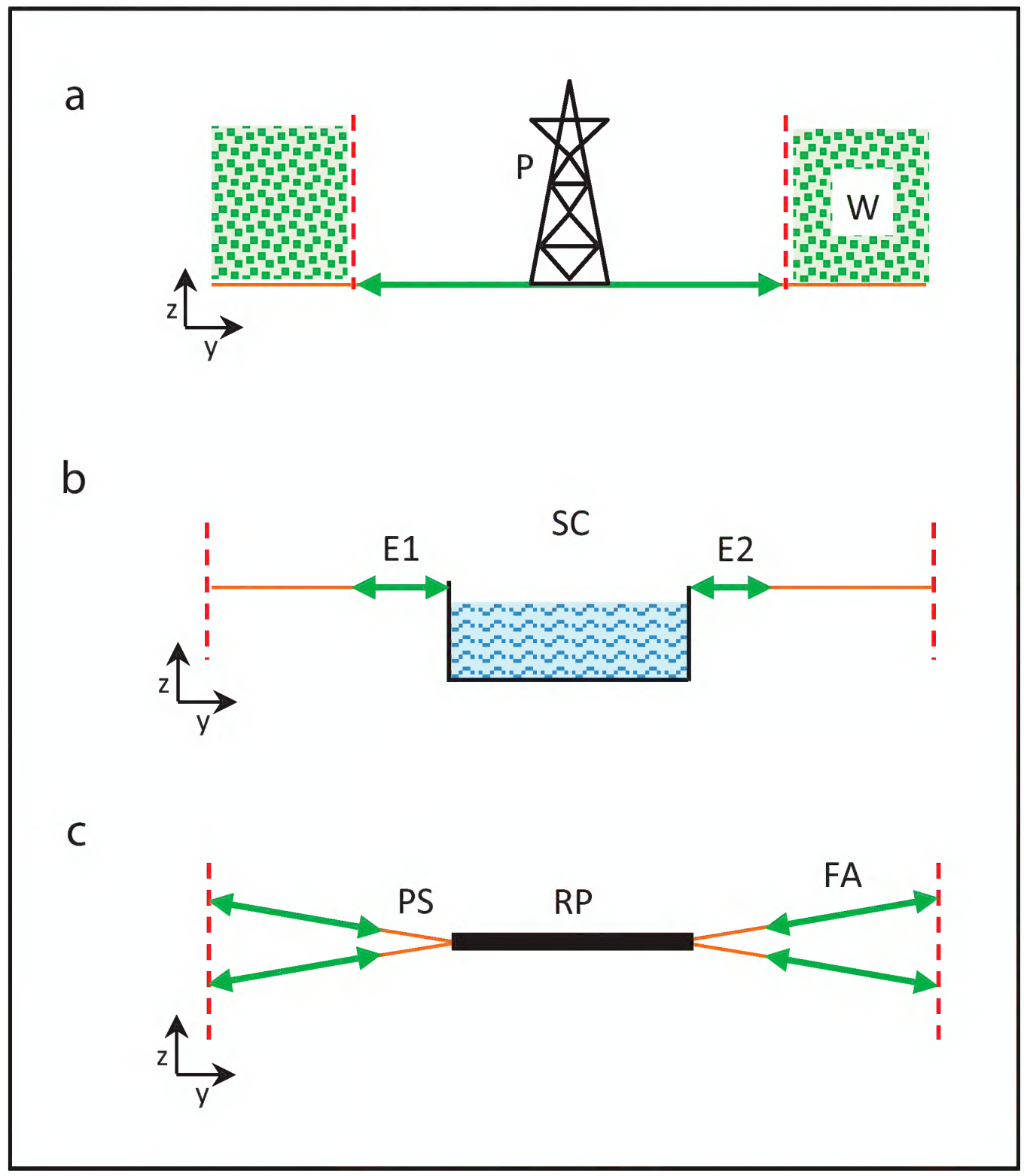

Figure 1. ROW cross-sections of **a** power lines **b** waterways (case of shipping canal) **c** railways and roads. Caption: Dotted red line: side boundaries of the entire ROW; Brown line: ground surface; Double green arrows: extent of ROW portions considered in the estimate; P: pylon; W: wooded area; SC: shipping canal; E1 and E2: easements of waterways; RP: railway or road platform; PS: proximity/safety strip; FA: far area.

Figure 2. Dry grassland hosting a protected species (*Gagea pratensis*) in a power line ROW, in the center of France (47.8644°N, 1.8076°E).

The rules for delineating the outer boundaries are defined by law (Etrillard 2019). At this study scale, it was not possible to consider a detailed analysis of the actual width of all waterway rights-of-way, nor was it realistic to estimate a representative average width, for both artificial and natural waterways.

In contrast, for technical servicing purposes, two regular strips of land are reserved on both sides of waterways (Fig. 3). The broader one is the towpath easement (7.80 m wide – i.e. 24 feet), while on the opposite bank a 3.25 m-wide land strip (10 feet) is reserved for operators, fishermen and pedestrians. With the aim of providing a realistic floor value, the minimum legal ROW width (rounded to 11 m) was thus adopted for this calculation.

Figure 3. A shipping canal right-of-way with its towpath in the foreground, in the north of France (50.9400°N, 2.2622°E).

Railways

Railway types considered in the estimate

Four types of railway infrastructure were considered for this estimate: high-speed rail network, main railway lines, service track, and unused track.

In BD TOPO®, high-speed lines are defined as being reserved for high-speed trains and are referred to as LGV (for *Ligne à Grande Vitesse*). The main railway lines correspond to all lines in operation that provide regular or seasonal service transporting passengers or goods, with the exception of LGVs. The database solely considers service track to extend more than 200 m in length and the definition excludes track segments included in a bundle of lines more than 25 m wide (e.g. marshalling yards), as well as subterranean track. As regards unused track (defined as declassified and closed to any kind of traffic), the database also solely considers segments more than 200 m long; subterranean segments are also excluded.

All railway lines are bordered by so-called “proximity strips”, where for technical and safety reasons vegetation is strictly controlled throughout the year to keep it short, by means of mowing or chemical weed treatment (Michel et al. 2015). For LGVs, this strip is 4 m wide on both sides, whereas 3 m is the width for both the main railway lines and service track.

In order to more easily maintain higher speeds, the longitudinal profile of LGVs needs to be as flat as possible, hence the land’s natural relief may be

Figure 4. A LGV right-of-way with embankment in a hilly landscape, in the east of France (47.3370°N, 6.0075°E).

highly modified by earthworks. Compared to the main railway lines, this leads to higher embankments and deeper cuts to enable high-speed lines to pass through the landscape (Fig. 4). Hence, all along LGVs, the ROW width varies to follow changes in the natural relief. Maximum width is found at both the top of cuts and bottom of embankments; the minimum occurs where the longitudinal profile of the track (called the red line) coincides with the natural topography.

Estimates of railway rights-of-way average widths – Influence of topography

In France, the red line very rarely coincides with the natural relief. For the purposes of this estimate, an average reference width for the LGV right-of-way in France was sought. In order to estimate a realistic value, previous studies on geometry and earthwork slopes (Ginot et al. 2010; Fargier 2013) were combined with aerial view observations (Géoportail cross-referenced with Google Earth), for slightly rolling landscapes crossed by LGVs. It appears that the minimum side width for LGVs can be considered equal to 17 m (value for flat zones). For slightly rolling areas, the average LGV side width amounts to 41 m (derived from: vertical variations = ±6 m; earthwork slopes = 2/1; plus the previous 17 m). Main railway lines and service track (as well as unused track) do not necessitate such major earthworks. Based on the same technical references and map observations (Géoportail and Google Earth), their average side width was set equal to 15 m.

Consequently, for LGVs, depending on topography, the average ROW width potentially available as an ecological shelter (i.e. the so-called “far area”), is 9 m (minimum value corresponding to a theoretically flat topography) and 33 m (average relief). For main railways, service and unused track, this value is 9 m (average relief).

Roads

Road types considered in the estimate

Three types of road infrastructure were considered for this assessment: the motorway network, the so-called “quasi-motorway” network, and the dual carriageway road network.

Figure 5. A motorway right-of-way (proximity strip and far area), in the west of France (47.0602°N, 1.4243°W).

In BD TOPO®, motorways are defined as "roads without crossings, accessible only at points set up for this purpose and reserved for power-driven vehicles"; and are classified as such by decree of the Council of State. Quasi-motorways satisfy the same technical definition as motorways (carriageways separated by a central median, no at-grade intersection with the rest of the road network) but are not officially classified as such. Dual carriageway roads have two pavements separated by a physical obstacle that may open at grade intersections. The presence of intersections prohibits them from being classified in either of the previous categories.

Roads are bordered with a strip of land where, for technical and safety reasons, vegetation is strictly controlled throughout the year (Michel et al. 2015). The width of this safety strip (Fig. 5) can vary slightly from one manager to the next, but for the main road networks (motorways, quasi-motorways, dual carriageway roads), the minimum is 4 meters (François and Le Féon 2020).

Similar to LGVs, to allow for higher speeds, motorway longitudinal profiles also result in many embankments and cuts in the natural topography. However, motorways can comply with steeper slopes than LGVs (maximum slope of 6% vs. 3.5% (Ginot et al. 2010)), which leads to smaller cuts and embankments, hence narrower ROW in rolling landscapes.

Estimates of road right-of-way average widths – Influence of topography

An average reference width for motorways and quasi-motorways was sought. To estimate a realistic average width for their rights-of-way in France, documentation on their geometry and earthwork slopes (Ginot et al. 2010) was combined with aerial view observations (Géoportail and Google Earth) for slightly rolling landscapes. For (quasi-)motorways, the minimum value of total ROW width thus amounts to 8 m (with no topographic changes) and for medium hilly areas, the average width is 24 m (derived from: vertical variations = ±4 m; earthwork slopes = 2/1; plus the previous 8 m).

In order to characterize the average total ROW width for dual carriageway roads, map observations were carried out over 44 cross-sections from 7 such roads across the country. This led to an average minimum right-of-way width of 10 m. In considering the ROW width variations along these road sections (often

above 20 m and up to 25 m) and the average width for each one (9 to 19 m), a value of 16 meters has been selected to characterize the average total right-of-way width for dual carriageway roads.

It appears that for (quasi-)motorways, the average ROW width potentially available as an ecological shelter (the "far area") equals zero in the theoretical case of flat topography, and 16 m in the case of average relief. For dual carriageway roads, figures are respectively 2 m and 8 m. These areas are part of road verges, defined as the vegetated area adjacent to roads (van der Ree et al. 2016).

Road medians and interchanges

The re-vegetation of road medians with attractive plants in the aim of creating a habitat and/or kind of stepping stone between both sides of the infrastructure is regarded as a counterproductive initiative with respect to flying insects, such as bees, butterflies and dragonflies, responsible for more collisions (Keilsohn et al. 2018; François and Le Féon 2020). Accordingly, this kind of ROW has not been included in the calculation of PES. Moreover, in France, medians are generally far narrower than twice or even one times the safety strip (i.e. 4 m). With respect to this same crossing issue, motorway interchanges and their associated verges were not considered in the estimate: for one thing, they create isolated green areas and for another, their inclusion in the calculation would falsely increase the length of road sections with PES. All these sections were differentiated thanks to their referencing as "Ramp" in BD TOPO®.

Results

The detailed figures for the entire estimate are provided in Table 1. For each subtype of transport infrastructure are given: the length of potential ecological shelter, the share of the total PES network this represents, the width of ROW considered in the calculation and the surface area of ecological shelter.

Table 1. Features of the potential ecological shelter offered by the various LTI networks in Metropolitan France.

LTI type	Subtype	Length (km)	Share of total linear (%)	Width (m)	ROW share[a]	Surface area (km²)
Power lines	High voltage	13,347	15.2	24	Entire width	320
	Very high voltage	20,652	23.4	50	Entire width	1,033
Waterways	Shipping canals	3,603	4.1	13	E1 + E2	47
	Navigable rivers	3,991	4.5	13	E1 + E2	52
Railways	High-speed lines	1,839	2.1	33	FA	61
	Main railways	24,035	27.3	9	FA	216
	Service track	1,430	1.6	9	FA	13
	Unused track	2,868	3.3	15	PS + FA	43
Roads	Motorways	10,276	11.7	16	FA	164
	Quasi-motorways	3,481	4.0	16	FA	56
	Dual carriageway roads	2,572	2.9	8[b]	FA	21

[a] See Figure 1.
[b] The dual carriageway roads for width measurements were N4 around Vitry-le-François (48.726°N, 4.585°E), N12 around Dreux (48.736°N, 1.370°E), N42 around Boulogne-sur-Mer (50.725°N, 1.613°E), N154 around Evreux (49.027°N, 1.511°E), CD83 around Colmar (48.079°N, 7.358°E), CD 775 around Segré (47.689°N, 0.868°W), and CD 824 around Dax (43.708°N, 1.051°W).

Linear extent of potential ecological shelter

Linear extent of PES along LTI networks

Power lines provide the greatest length of PES (33,999 km in all). This value accounts for approximately one-third of the total length of transportation networks managed by the national operator (100,000 km in Michel et al. 2015; 105,500 km calculated from BD TOPO®). The total linear extent of PES along waterway network (7,594 km) is nearly equally split between shipping canals (47%) and navigable rivers (53%). Railways provide the second greatest length of PES (30,172 km total). LGVs constitute just 6% of the total for railways, while the vast majority (79%) stems from the densely-branched main railway network. Unused track is next with nearly 10% of the total, and service track offers the least length, with some 5%. Regarding roads, the total length of PES (16,329 km) is principally provided by motorways (63%). Aside from the classification issue (motorway vs. quasi-motorway), the overall length for this type of infrastructure (i.e. (quasi-)motorway) amounts to 13,757 km, i.e. 84% of the total potential ecological shelter along road network. Dual carriageway roads cover the remaining 16%. As a result, the total length of PES along the four LTI networks in Metropolitan France is 88,094 km.

Share of the different LTIs in the total PES linear extent

Power lines are the most extensive part of the total PES network (38%, Fig. 6), slightly ahead of railways (34%), with the main railway lines alone accounting for 27% (the leading LTI subtype). By definition, the power lines of interest for PES are generally localized in remote large forested areas, whereas the densely-branched main railway network encompasses almost all parts of the national territory. The road network is the next most extensive LTI (at 19% of the total), of which (quasi-)motorways represent by far the majority share (a combined 16%). Lastly, the waterway network accounts for 9% of the total yet is more concentrated in certain regions (e.g. Northeast). This ranking with respect to network extent differs from that based on the number of studies and research

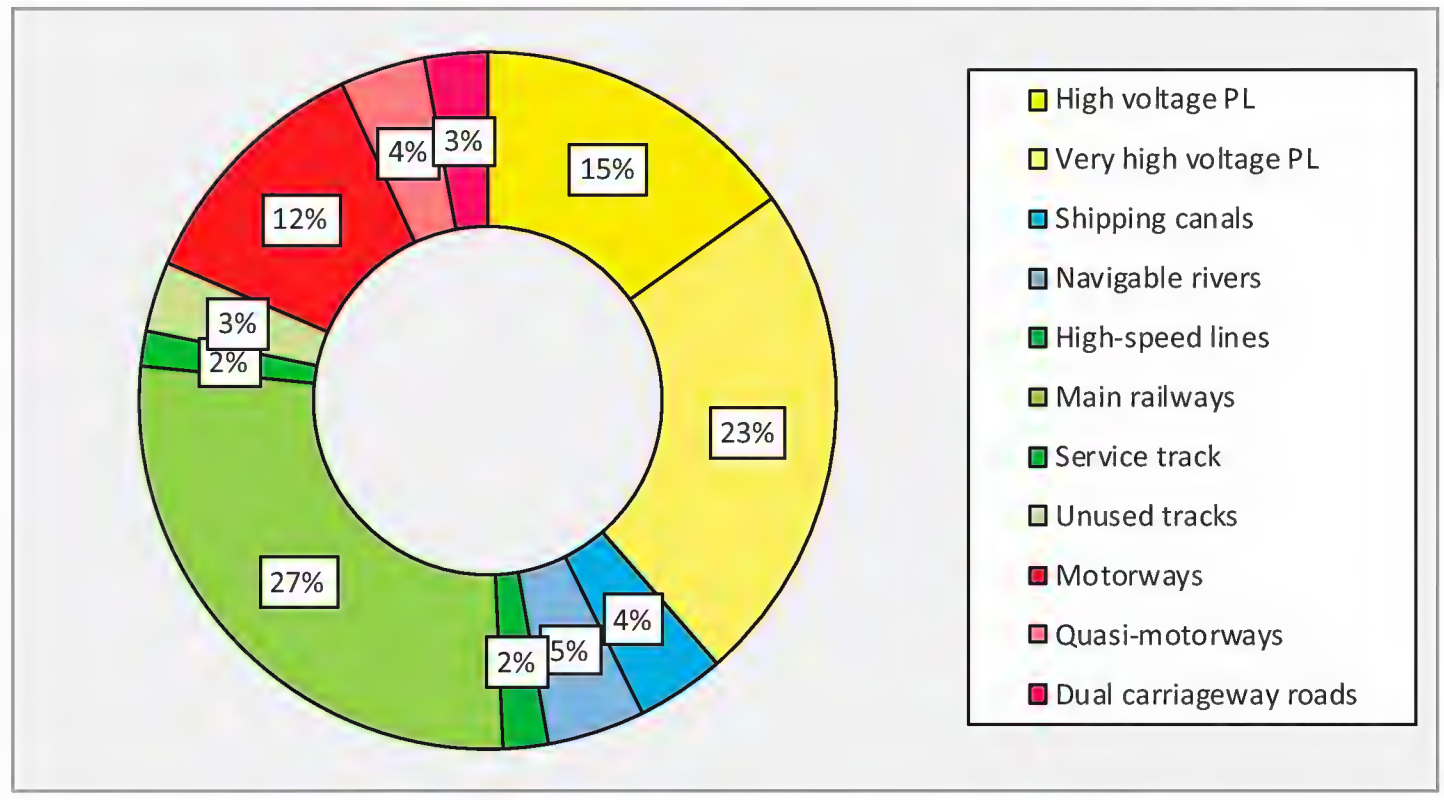

Figure 6. Share of the different LTIs and their subtypes in the total linear extent of PES at national scale.

carried out until now on LTI rights-of-way for insects in temperate regions, where roads come in first place, followed by power lines, with both railways and waterways receiving limited attention (Villemey et al. 2018).

Surface area of potential ecological shelter

Surface area of PES along LTI networks

The surface area of ROW under HV lines in forest corridors amounts to 320 km^2. The value for VHV lines (longer network and wider cuts) is significantly larger: 1,033 km^2. The total surface area for power line ROW represents 36% of the total ROW surface reported by the national operator (i.e. 4,000 km^2 in Michel et al. 2015). The surface areas of potential ecological shelters bound to shipping canals and navigable river easements accounts for 47 km^2 and 52 km^2, respectively. Considering the average cross-section of LGVs through slightly rolling landscapes, the surface area of PES amounts to 61 km^2. Due to the large extent of the main railway network across interurban areas, the surface area of PES increases to 216 km^2. With the same typical cross-section (i.e. 9 m of ROW width), service tracks account only for 13 km^2. Unused tracks (15 m of ROW width) account for 43 km^2. Considering the average cross-section of motorways and quasi-motorways through slightly rolling landscapes, the surface area of PES amounts to 164 km^2 and 56 km^2, respectively. Lastly, for dual carriageway roads, considering the average cross-section, the surface of PES equals 21 km^2. As a result, the total area of PES along the four LTI networks in Metropolitan France is 2,026 km^2.

Share of the different TLIs in the total PES surface area

Power lines provide the highest share of the total PES surface area (67%, Fig. 7) with VHV power lines as leading LTI subtype (51%), far ahead of railways (17%), with the main railway lines alone accounting for 11%. The road network is next (12%) of which (quasi-)motorways represent by far the majority share (a com-

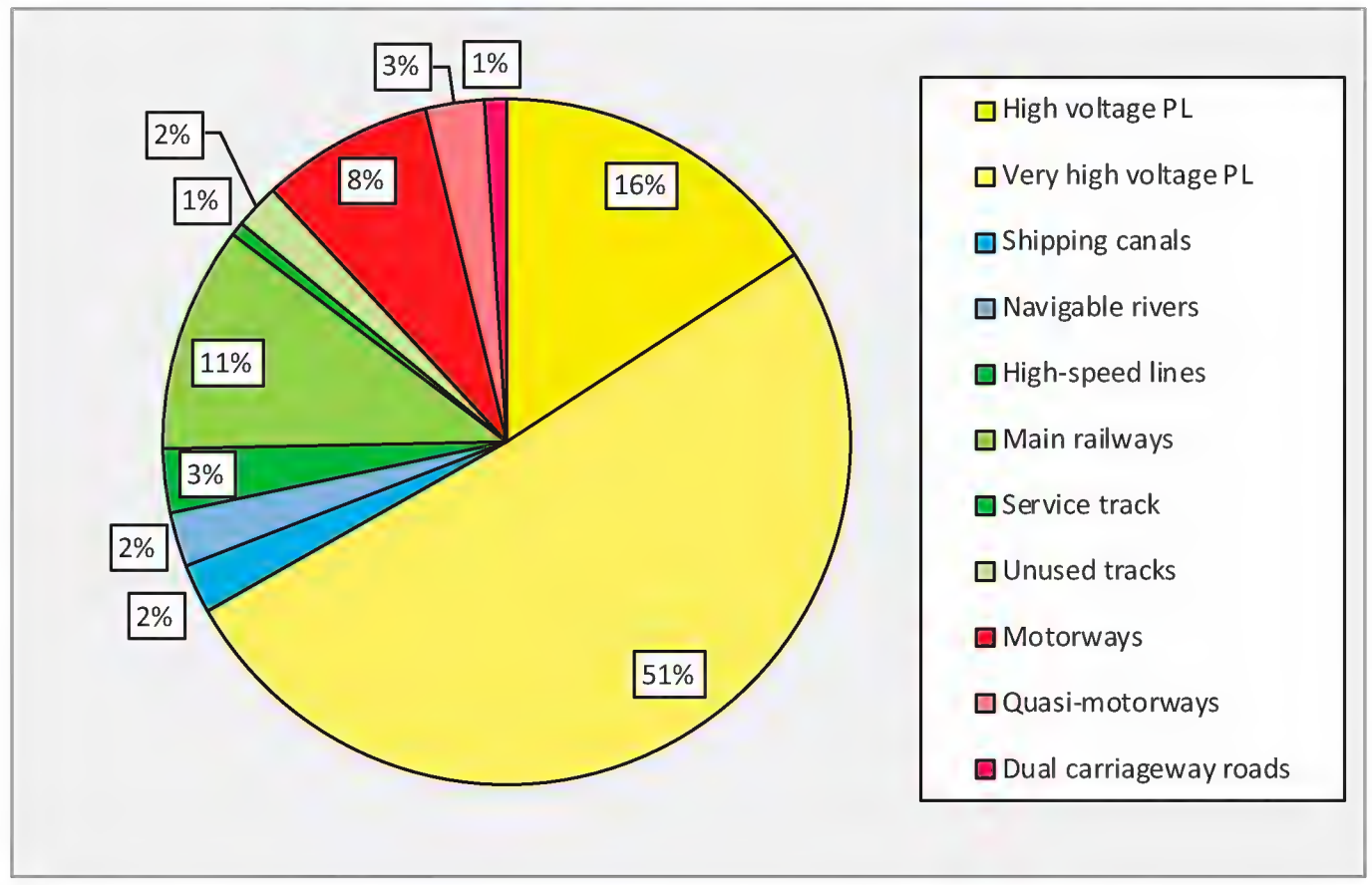

Figure 7. Share of the different LTIs and their subtypes in the total surface area of PES at national scale.

bined 11%). Lastly, the waterway network (for which only easements have been considered) accounts for 4% of the total surface area.

This PES surface floor value is just a small fraction (i.e. about a third) of the surfaces indicated by the various LTI operators for their full ROW asset, which amounts to approximately 5,900 km^2; excluding the surface area of the national road network asset, not yet accurately estimated (NNCM 2009; Michel et al. 2015). These large figures include narrow road verges, proximity strips, ROW located in urban and industrial zones, isolated surfaces inside interchanges and road medians.

Discussion

Potential ecological shelter bound to power line network

Linear extent and surface area features

The larger proportion of VHV lines (20,652 km), compared to HV lines (13,347 km), stems from the former being located further from power distribution (i.e. urban) areas, thus more conducive to crossing large wooded areas. Besides, just 25% of the total length of HV lines (53,500 km calculated from BD TOPO®) are located in forests, compared to 40% for VHV lines (total length: 52,000 km). The electricity transmission operator (RTE), a single national entity, does not own the ROW, which remains the property of the landowner (private, municipal or national forests) (Etrillard 2020).

Current management of ROW

As a general rule, the operator substitutes for the landowner in maintaining ROW vegetation. He determines the maintenance techniques and tree cuts performed to ensure the safety of the power lines, yet the cut vegetation remains the landowner's property (Etrillard 2020). Rotary-slashing is the most widespread maintenance practice today for ROW vegetation, with one pass every 3–5 years, which often benefits fern colonization to the detriment of plant diversity (François et al. 2018). Other ROW maintenance modes are possible (oriented for instance towards pastureland, hay meadows, conservatory orchards or the restoration of natural open habitat) and generally based on local partnerships (Godeau 2018; Etrillard et al. 2019). Studies carried out in several accommodating forest power line ROW, in the USA, Sweden and France, have demonstrated their potential for sheltering varied communities of wild bees and butterflies (including rare and even reputedly extinct species) and for landscape connectivity for these insects (Russell et al. 2005; Wagner et al. 2014; Berg et al. 2016; François et al. 2018).

Potential ecological shelter bound to waterway network

Linear extent and surface area features

As regards shipping canals, most of the length (i.e. 3,175 km) is part of the network managed by the State operator (VNF), notably for heavy transport, while the remainder (428 km) is by various local authorities and mainly dedicated to recreational boating. As regards navigable rivers, the breakdown between

the State operator and local authorities is more evenly balanced: 2,087 vs. 1,904 km, respectively. For control purposes, the total length of the public waterway domain was estimated with BD TOPO®: the result (6,480 km) differs by just 3% from the figure indicated by the State operator (6,700 km in Michel et al. 2015). It appears that over 80% (i.e. 5,262 km) of the VNF network length presents PES. With respect to the total 2,707 km of non-State waterway network, compiled by querying BD TOPO® and consulting network maps, more than 85% (i.e. 2,332 km) of the entire length presents PES.

Surface areas of PES bound to shipping canals and navigable rivers are divided between the public fluvial domain under State responsibility on the one hand and the non-State domain (riparian owners and local authorities) on the other. The State 68 km^2 are split between shipping canals (41 km^2) and navigable rivers (27 km^2). For the non-State domain, 25 km^2 are bound to navigable rivers and just 6 km^2 to shipping canal easements.

The total surface area of 99 km^2 is the floor value for the PES along waterway network. For navigable rivers, a strip of land can extend between the towpath and the river shore. Its width varies seasonally with the river level and may be used for cattle grazing (Etrillard et al. 2019). Similar to navigable rivers, the shipping canals ROW can also extend to the sides, at varying distance from the towpath. The national operator (VNF) indicates that the entire asset entrusted to it by the State amounts to approx. 400 km^2 (Michel et al. 2015), which covers not only the total easement surfaces calculated in this estimate (83 km^2 when urban areas are taken into account) and the aforementioned additional ROW width, but also annex areas such as the numerous former dredging sediment deposit areas, some of which have been colonized by nature (VNF 2015).

Current management of ROW

The most widespread current technique for vegetation maintenance on easements and their vicinity is grass mowing with a rotary-slasher, at least once a year (higher frequency in more anthropized areas). The common practice is to leave the cut grass on the ground. However, some experiments with pasture (sheep, cattle) have been implemented along waterway easements by means of partnerships with shepherds and farmers (Etrillard et al. 2019). For some shipping canals, banks have been vegetated to create aquatic habitat (VNF 2015).

Potential ecological shelter bound to railway network

Linear extent and surface area features

Compared to the figure provided by the national operator (SNCF) in 2015 for all operated lines (29,273 km in Michel et al. 2015), the estimate calculated from BD TOPO® for the total LGVs plus main railways (including within urban/industrial areas) differs by just 5% (30,814 km). In fact, in the span of time some main lines may have been closed and the high-speed network has increased slightly (2,141 km according to calculation vs. 2,024 km according to Michel et al. 2015). Logically then, since LGVs are designed to link distant conurbations, over 85% of high-speed network length offers PES. The ratio is similar (84%) for the extensive and highly-interconnected main railway network (total length

calculated: 24,035 km). Service track is primarily located adjacent to activity centers in urban/industrial areas: consequently, just 18% of the total length in this LTI type (i.e. 8,095 km calculated from BD TOPO®) presents PES. Lastly, a large share (59%) of the total network of unused track (i.e. 4,857 km) contains PES. This part of the network typically corresponds to abandoned track located in low-density rural areas. It has been observed that disused railway lanes can foster the emergence of hedgerows, which serve as habitat and corridor for local flora and fauna (Carlier and Moran 2019). Like the rest of the railway network, unused track remains under the responsibility of the national operator, as long as these sections are not declassified. Declassification is rare and generally proceeds in the case of specific requests by a potential buyer and when it is absolutely certain that the given section will never again be used as a railway or even any other transportation purposes (e.g. bicycle path, greenway).

The total surface area of PES along railway network (333 km^2) is far lower than the figure provided by the national operator (SNCF) in 2015 for its total green areas (600 km^2 in Michel et al. 2015). The addition of the proximity strip on all interurban lines considered in this estimate (6 to 8 m depending on the line type) increases the railway side surface to 500 km^2. The gap with the operator's total figure can easily be filled by the rights-of-way located in conurbations (network estimated at 13,594 km) as well as to the sum of all rights-of-way much wider than the minimum average considered herein, e.g. when LGVs cross hilly landscapes.

Current management of ROW

The outermost part of railway ROW (i.e. the verge) is managed to maintain mixed vegetation (herbaceous and woody), with an emphasis on controlling wooded vegetation (shrubs and particularly trees) for various safety reasons (falling wood and leaves on the trafficked section, destabilization and monitoring of embankments) (SNCF Réseau 2017). Woody vegetation is generally maintained by means of mechanical brush clearing every 3–5 years. The management is more intensive on high-speed lines and leads to more grassy sides than on the rest of the railway network. Similarly to other LTIs, sheep grazing experiments are currently being conducted on grassy rail verges.

In general, unused track is left to the progressive recolonization by ruderal vegetation and this can be an opportunity for the natural reestablishment of hedgerows in some landscapes. Over time, the former verges can be replaced by trees, while the central area with old ballast offers more difficult soil conditions (rocky, dry, macro-porous), conducive for some shrubs and bushes. These wide hedgerows can provide shelter and resources to local flora and fauna (Carlier and Moran 2019).

Potential ecological shelter bound to road network

Linear extent and surface area features

For motorways, most length is managed by concessionary companies (8,088 km - i.e. 78% of the total), with the remainder (2,188 km) being by State services. Quasi-motorways, as well as dual carriageway roads are operated by public bodies, either State or local authorities. Since the motorway network is

designed for long-distance interurban transportation (similar to LGVs), it is not surprising that 90% of its total length (estimated at 11,432 km from BD TOPO®) presents PES. This ratio is also high for quasi-motorways (over 75%), but shows however that for this road type, a higher fraction is located in conurbations (total length calculated from BD TOPO®: 4,597 km). As for dual carriageway roads, the fraction showing PES is 46% of total network length (i.e. 5,561 km): this reflects that an even higher fraction of this last road type is in conurbations.

For motorways, nearly 80% of the surface (129 km^2) is maintained under the responsibility of private concessionary companies, with the smaller portion (35 km^2) being under State services. The quasi-motorway sections considered in the estimate (i.e. exurban areas) are maintained by State or local authorities (i.e. department) services. Twenty years ago, the total surface of motorway verges was estimated at 160 km^2 by Meunier et al. (1998). Calculation details were not provided, but considering that in 1997 the total motorway network spanned 8,864 km (CGDD 2019), the average motorway verge width value would be 18 m. In complementing our present calculation with the two safety strips (a combined 8 m) applied to 10,276 km (Table 1) and the urban motorway network (1,156 km calculated from BD TOPO®), the total motorway verge surface amounts to 256 km^2. For the entire motorway network (11,432 km), this would suggest a theoretical average verge width of approx. 22 m, hence 4 m more than Meunier et al.'s 1998 estimated average value.

Current management of ROW

The most widespread technique for road verge vegetation maintenance is grass mowing with a rotary-slasher, generally carried out once a year as regards the outer ROW part, considered herein. Late mowing is becoming more popular among operators nowadays in order to preserve the biological cycle of flora and associated fauna. However, the cut grass left to decompose on the ground remains an obstacle to the establishment of a diverse flora and supporting insect populations (François and Le Féon 2020). For quite some time, road verges have proven to be as potentially as biodiverse as hay meadows (De Redon de Colombier 2008). The controls applied to woody vegetation are more stringent on high-speed roads ((quasi-)motorways) and generally require trees and shrubs to be situated further from the proximity strip than on classical dual carriageway roads.

Key right-of-way features with implication for ecological management

Generally, in wooded areas, power line rights-of-way are cuts made in preexisting forests. However, in some areas where the forest is expanding today due to the disappearance of pastureland, the maintenance of power line ROW keeps open parts of this former environment, such as dry grassland (François et al. 2018), particularly favorable to flora diversity and pollinating insects (Krauss et al. 2009; Jauker et al. 2013).

The broad width and virtual absence of human disturbance (limited access for people and minimum maintenance operations) for power line ROW are conducive for introducing livestock pasture, and thereby maintaining an open environment over the long term (Godeau 2018). The lateral boundary with closed to very closed environments (i.e. forest) creates a corridor linking the open environments

located at both extremities or connecting other corridors. Banks of shipping canals and navigable rivers offer similar conditions for livestock. However, there is a risk of disturbance to livestock from pedestrians and cyclists using towpaths, as well as a risk of drowning due to the proximity of water (Etrillard et al. 2019).

The commercial railway network (LGVs + main railways) and road network generate a comparable surface of PES (277 km^2 and 241 km^2, respectively). The size of these ROW surfaces was estimated using the same approach, i.e. the area between the proximity/safety strip and the outer ROW boundary in a slightly rolling landscape representative of the average situation of land crossed by such infrastructure in France. These two kinds of ROW are also similar, i.e. they are distributed on both sides of a broad section traveled by high-speed vehicles. In relation to connectivity, the aim of verge management for entomofauna must not be focused on crossing traffic zones, as this would increase mortality from vehicular collision (Kasten et al. 2016; Vinchesi et al. 2018).

The particular feature of railway and road rights-of-way regarding connectivity lies in their potential to connect segments of the surrounding (and original) green network. When the LTI was built, transverse corridors of the green network were severed. As a result, on each side, the remaining segments (e.g. hedgerows) often end on the outer boundary of a uniformly inhospitable ROW. Creating supporting habitat conditions inside rights-of-way to reconnect fragments of the local green network may facilitate species flow and gene flow within the landscape: far areas (Fig. 1) can be shelters for species (e.g. simple habitat patches), then bases for dispersal of populations in the surrounding landscapes (François and Le Féon 2020). This kind of ROW can also serve as a preferential corridor for flying insects as demonstrated in the case of bumblebees foraging (Hanley and Wilkins 2015). When foraging, bumblebees and honeybees have been shown to follow flight-paths free of transverse obstacles (Ohashi and Thomson 2009; Buatois and Lihoreau 2016). Moreover, good quality flower resource favours the movement of pollinating insects within road verges, rather than across the road (Dániel-Ferreira et al. 2021). Greater floral diversity and density in the far area as opposed to the proximity strip (Fig. 1) may reduce the attractiveness of the roadside to bees, thereby reducing the risk of collision mortality (François and Le Féon 2020; Dániel-Ferreira et al. 2022).

A revised involvement for LTI operators and local stakeholders

Involvement of local skills in ecological management

Awareness of biodiversity issues related to rights-of-way is becoming widespread among LTI operators (Michel et al. 2015). However, the primary function of LTI operators is to guarantee the level of service to users. They therefore remain above all technical operators who generally lack the required expertise to implement optimal ecological management of rights-of-way. In order to address this difficulty (at least in the short and medium term), LTI staff could be accompanied by local stakeholders with skills in the management and maintenance of natural or semi-natural environments. This ecological support could be formalized through suitable management partnerships. Such local stakeholders can be NGOs of various kinds, individuals in the field of agro-ecology notably (farmers, breeders), regional natural parks or even local authorities. A

small number of cooperative ventures along these lines have been, or are being, run in France; the lessons learned serve to strengthen their sustainability (Etrillard et al. 2019). These management partnerships would optimize organizational solutions combining stakeholders' legal, ecological and safety concerns. This solution helps address the wide diversity of opportunities that can arise within LTI networks across the country.

Contracting between operators and local stakeholders

According to the LTI, the partnerships involve the operator, stakeholders with environmental skills, but sometimes also the owner of the right-of-way (when the operator is not the landowner).

As regards all operated railway sections (i.e. LGVs, main railways, service track), ROW maintenance falls under the sole responsibility of the national network operator and belongs to the State-owned domain. Concerning roads, in addition to the 2,188 km of PES under the responsibility of State services (Potential ecological shelter bound to road network), 2,306 km of quasi-motorway and 1,613 km of dual carriageway roads are also counted in the State-owned domain. The other components (respectively 8,088 km, 1,175 km and 959 km) fall under the responsibility of concessionary companies or else belong to diverse local authorities (departments, local communities). As for waterways, the national operator's PES network (shipping canals + navigable rivers) extends over 5,262 km of State-owned domain while various local authorities manage the other part (2,332 km). Lastly, for power lines, the PES only extends over 711 km into State-owned forests (340 km and 371 km for HV and VHV lines, respectively), with by far the largest share located in private and municipal forests (13,007 km for HV lines + 20,281 km for VHV lines).

At the scale of Metropolitan France, the total PES along LTI networks under operations (i.e. with regular ROW maintenance), covers 85,226 km (the 2,868 km of unused railway track, generally left to be freely colonized by flora and fauna are considered separately). The State-owned domain hosts 46.2% of the operated asset. This share is made up of railways (32.0% - i.e. all the operated network), then comes 7.2% of roads, 6.2% of waterways and just 0.8% of power lines. Relative breakdown is depicted in Fig. 8. For State-owned rights-of-way, simple two-party agreements are required, between the public operator and its partner in charge of ecological management, for implementing actions to contribute to public biodiversity policies.

Non-State rights-of-way could be used in the same manner; they represent 53.8% of the total operated network with PES and develop over the domain of local authorities, private landowners or concessionary companies. This asset is mainly composed of power lines (39.1%), then roads (12.0% shared between local authorities – 2.5% and concessionary companies – 9.5%), and lastly 2.7% attributed to waterways (shared between local authorities and private landowners). For roads, in both cases, partnerships would require simple two-party agreements between the partner in charge of ecological management and the motorway concession company, or the local authority. The same would apply for waterways managed by local authorities. For power lines crossing communal or private forests, management partnerships would require a three-party agreement including the landowner (Etrillard et al. 2019).

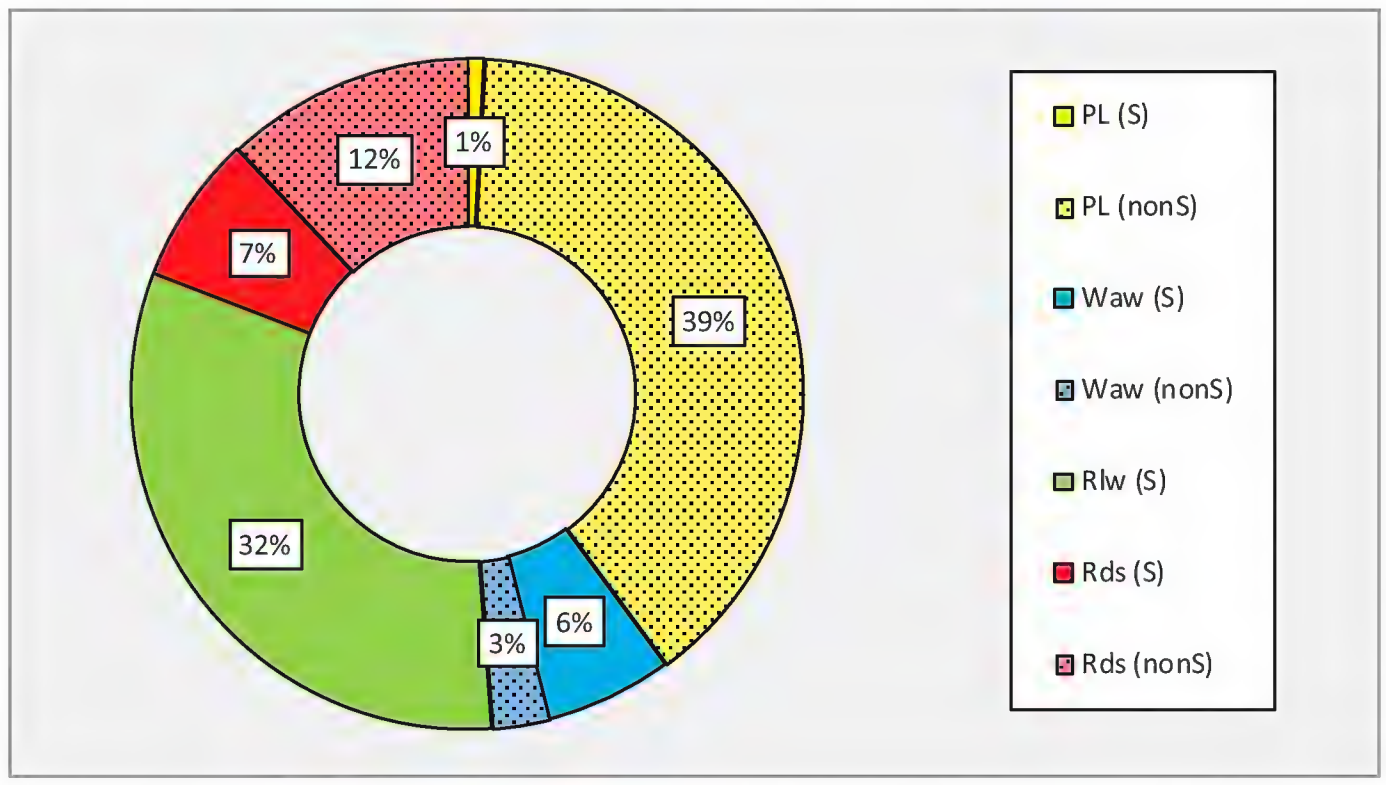

Figure 8. Share of potential ecological shelter between State-owned (S) and non-State-owned (nonS) operated networks (85,226 km). PL: power lines; Waw: waterways; Rlw: railways; Rds: roads.

Implementing national policy at local scale

The aim of the national asset estimate of PES is to provide a sound basis for an informed policy for the contribution of LTI to biodiversity conservation at national scale. Databases suitable for estimating the surface importance of PES and their ownership have been chosen in virtue of their properties of accessibility, completeness and consistency of data at broad scale. On the operational local level, the policy (local authorities) and action (field stakeholders) will require precise mapping, using more detailed data and field checking. They will take into account the specific local issues. Local mapping will enable to precisely draw the PES areas, measure their interdistances and identify their proximity to elements of the surrounding green and blue network, outside the ROW. In addition to the restoration of good habitat condition for local species within PES, this will highlight opportunities to develop stepping stones of habitat patches thanks to PES and to re-establish/develop connectivity with the surrounding landscape (François and Le Féon, 2020).

Conclusion

When a landscape has been damaged by fragmentation and destruction of its natural habitat, whether this is mainly attributable to linear transportation infrastructure or to other causes, LTI rights-of-way can, to a certain extent, provide shelter to the local flora and entomofauna through habitat and conduit functions. To optimize the use of this potential of LTI rights-of-way toward achieving a consistent and efficient conservation strategy, it is necessary to know the extent of surfaces actually suitable for developing a relevant action plan, along with the network length and spatial distribution.

Based on scientific evidence gained in recent years, ROW potential to support biodiversity is now being recognized as a viable possibility, to not only mitigate damages but also to restore local flora and fauna. However, awareness of this potential is more recent among many operators and landowners, hence ROW surface measurements in this specific aim are virtually nonexistent to-

day. The estimate of ecological shelter potential at the national level cannot be achieved by means of simply summing local data. On the other hand, calculations based on the total length of LTI networks at the national scale would lead to gross overestimation (in terms of both length and surface area). Any kind of LTI does, in fact, present sections located in inappropriate areas for habitat and connectivity restoration, and in some cases rights-of-way are inappropriate due to their isolation or narrowness.

If cartographic databases are available at the national scale for LTI networks and land use, GIS can then provide assistance in estimating the anticipated figures, and also identify local ROW sections of interest. A GIS-based method was developed for estimating the linear extent of PES for the various types of LTI networks, as well as their respective surface areas. Calculation assumptions have been illustrated by the French context (geometric criteria of LTI cross-sections and maintenance rules for the different ROW types), but the method is adaptable and transposable to all digitally-mapped territories.

At the scale of Metropolitan France, the total linear extent of LTI networks with PES has been estimated at 88,094 km, with the largest share being for power lines (≈38%), followed by railways (≈32%), roads (≈19%) and waterways (≈9%). Each type of LTI right-of-way presents particular features that determine its ability to serve as habitat, conduit and source for the surrounding landscape, hence its ability to contribute to reconstitute green and blue networks. PES associated with railway and road networks are more evenly distributed across the country than those associated with waterways and power line networks. The minimum total surface of PES has been estimated at 2,026 km^2. While the estimates for power lines (1,353 km^2), railways (333 km^2) and roads (241 km^2) result from a sound estimate of their typical cross-sections, for waterways just a floor value based of regular easements has been calculated (i.e. 99 km^2). A specific analysis would be necessary to approximate the full PES surface of waterway networks at the national scale.

The ecological shelter potential of rights-of-way could support the conservation of common, as well as threatened flora and entomofauna. Managing rights-of-way as an ecological shelter represents a new perspective and commitment on the part of all public and private LTI operators, with implications that extend beyond their traditional core business. This perspective can also mandate new requirements and responsibilities from and for public and private landowners in pursuit of optimal ROW use. In Metropolitan France, the State is the primary landowner of PES along operated networks, which also means that over half of the assets (53.8%) fall under the responsibility of local authorities, private agents and concessionary companies. The involvement of these stakeholders could be supported in the field by means of management partnerships for suitable ROW maintenance with local actors of green and blue networks and with authorities in charge of environment and transportation, who for their part could design national or regional strategies from the figures provided by this estimation method.

The networks and total surface areas of ROW managed by LTI operators are much higher than the linear extent and surface area of potential ecological shelter. In a general way, the most biodiversity-friendly maintenance as possible must be implemented within rights-of-way. The potential ecological shelter is the most protective part of the whole asset for biodiversity with regard to disturbance factors linked to the operation of infrastructure. This is where

stakeholders can engage the most ambitious and effective biodiversity conservation actions, as could be done under national/regional action plans, for wild pollinating insects notably.

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Conflict of interest

The authors have declared that no competing interests exist.

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Author contributions

François D: Environmental management, Ecology ; Medous L: Geography; GIS ; Etrillard C: Environmental law; Territorial units

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Data availability

All of the data that support the findings of this study are available in the main text.

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